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DEMONSTRATE THE FEASIBILITY OF A DETECTION METHOD TO SEPARATE NEUTRAL PARTICLES FROM CHARGED PARTICLES IN THE MEV/NUCLEON ENERGY RANGE

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Demonstrate the Feasibility of a Detection Method to Separate Neutral Particles from Charged Particles in the MEV/Nucleon Energy Range, by Bronislaw K. Dichter and Frederick A. Hanser

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A breadboard model of a spacecraft borne instrument to measure the neutral atomic fluxes with energies between 1 to 10 MeV/nucleon has been designed and constructed. Differentiation between incident charged and neutral particles will be done by measuring the production rate of convoy electrons by the particles. Calculations indicate that convoy electron production rate is much larger for neutral hydrogen than it is for protons. Incident particles strike a thin carbon foil at the entrance aperture and the resulting convoy electrons are identified using a 180° magnetic spectrometer with a micro channel plate detector at the focal plane. Incident beam particles pass through the spectrometer undeflected and are detected by a solid state detector. The instrument is designed to be tested at accelerator facilities with proton and neutral hydrogen beams. Neutral beams will be generated by passing a proton beam through a thin carbon foil and selecting the resulting neutral beam particles using a dipole bending magnet downstream of the foil.

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1. INTRODUCTION

The detection and identification of neutral particles such as hydrogen or helium, with energies of 1 MeV/nucleon and higher, by spacecraft borne instruments is likely to become important in the future. Solid state detector telescopes can readily detect incident neutrals, but since all incident atomic ions and neutrals rapidly achieve charge state equilibrium upon entering matter, it is not possible to distinguish between incoming neutral and charged particles solely with solid state telescopes. Neutral and charged particles can be separated by electric and magnetic fields. In the MeV/nucleon range, however, this method requires strong fields over large distances, and it is not suitable for spacecraft instruments where weight and size are generally limited. This report describes the progress made in designing and testing a comparatively small and light weight detection system that can statistically separate neutral and charged particles. The possible uses of such a system are to monitor space based tests of neutral beam systems, to monitor the exposure of satellites to neutral particle beams and to monitor the naturally occurring neutral particle flux in space.

The instrument, described fully in Section 1, uses a solid state detector telescope to measure the energy and identify the nuclear charge, and in some cases, the mass number of an incident particle. In addition, a magnetic spectrometer is used to detect energetic, forward moving electrons ("convoy electrons") produced by the passage of the incident particle through a thin carbon foil located in front of the detector. The "convoy electron" yield is expected to be much larger for incident neutral particles than it is for incident charged particles. This difference in yield can provide the desired signature of incident neutral particles.

The objectives of this contract can be summarized as follows:

a) Design and construct an instrument capable of simultaneously detecting and measuring the energy of both the electrons ejected from a thin carbon foil by a fast incident particle and the particle itself.

b) Test the instrument at an accelerator facility using a variety of beams and energies to learn under what conditions can the measurements described above be used to distinguish between neutral and charged incident particles.

c) Utilizing the results of the test, propose a design of a flight instrument which can be used to distinguish and measure neutral and charged particle fluxes in space.

2. GENERAL INSTRUMENT DESIGN

2.1 Breadboard Instrument

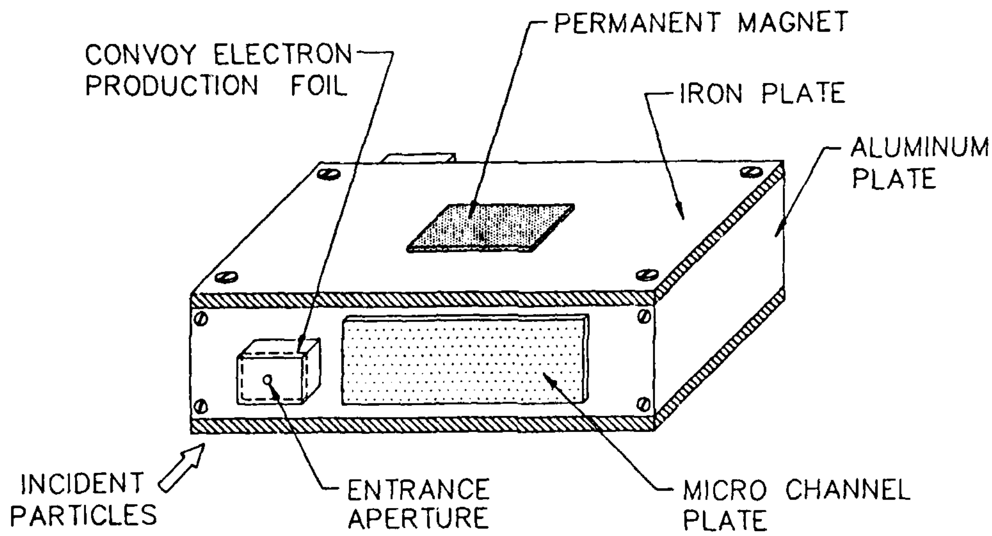
A breadboard instrument, to be used in the testing of the concept of neutral particle detection using accelerator beams, has been designed and fabricated. The mechanical construction of the detector is shown in Fig. 1.

Incident beam particles traverse the thin carbon foil (2-5μg/cm^2 areal density), move essentially without deflection through the magnetic spectrometer and are detected in the solid state detector. The forward going electrons produced by the passage of the beam particles through the foil enter the spectrometer. Their trajectories are bent by the magnetic field and the electrons impact on the Micro Channel Plate (MCP), which is mounted in the focal plane of the spectrometer. The MCP has a resistive, position-sensitive anode so that the location of the crossing of the focal plane by the electron trajectory (or, equivalently, its velocity) can be determined. The geometry of the spectrometer and the applied magnetic field is such that only electrons with velocities corresponding to energies greater than 0.5 keV will be detected in the MCP.

In the detector, as described in the technical proposal, the convoy electrons were to be detected by an array of four to five Channeltrons. Subsequent consideration of the detector requirements showed that the use of the MCP instead of the Channeltrons has several advantages. The two most significant advantages of the MCP over the Channeltron array are the much greater position resolution and much larger effective sensitive area. In addition, mechanical construction and electronic readout of the data become simpler as well.

The magnetic field of the spectrometer is provided by permanent NdFe magnets mounted on two 2" by 5" iron plates, separated by 1.5" aluminum spacers. The magnetic field is roughly perpendicular to the iron plates and its strength can be set to approximately 50 gauss by placing one magnet or 110 gauss by placing two magnets on each plate. The magnetic fields in both configurations have been carefully mapped out using a magnetometer. In particular, care was taken to measure the fringe fields and magnetic field components parallel to the iron plates so that a realistic calculation of electron trajectories could be performed.

The breadboard instrument has a single 200 mm^2 solid state detector located behind the spectrometer to detect beam particles coincident with electrons detected in the MCP. A flight instrument will need two such detectors arranged as a E-ΔE telescope. A telescope will be necessary because in orbit, unlike in an accelerator experiment, the identity of incoming particles is not known.



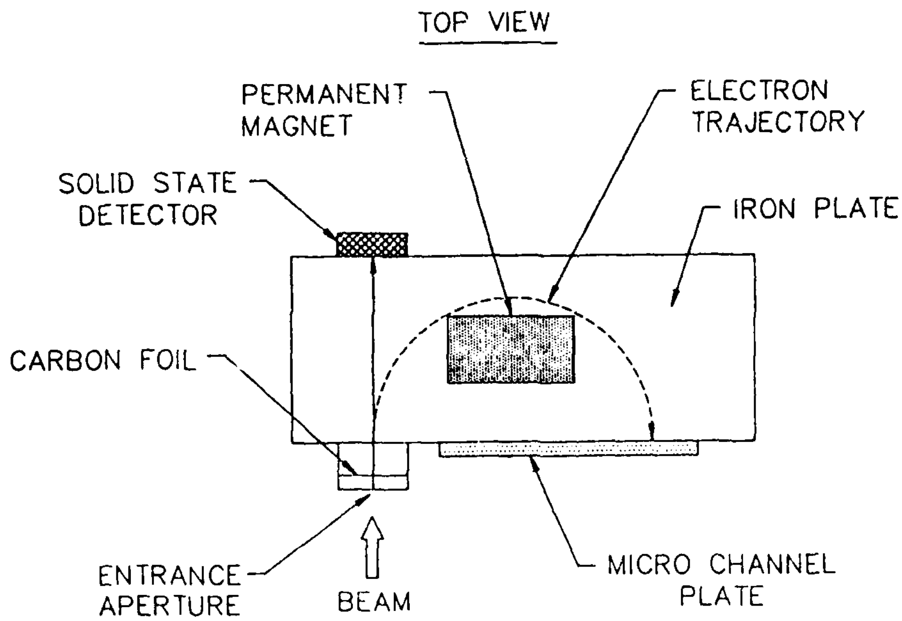


Fig. 1

Schematic diagrams of the neutral particle detector.

2.2 Accelerator Test Setup

The initial plan, as indicated in the technical proposal, was to perform the accelerator tests at the University of Pittsburgh nuclear structure laboratory. However, severe funding problems at that laboratory made it impossible for us to do our experimental work there. Therefore, arrangements were made for the use of accelerator facilities at University of Lowell and Yale University. The Van de Graaff accelerator at Lowell can produce proton beams with energies from 1 up to 4 MeV, while the ESTU Tandem Van de Graaff at Yale can produce proton and helium beams with energies from 5 to 40 MeV. The use of these two facilities will enable testing the detector over the entire energy range of interest.

Neutral and charged beams are necessary for testing and calibration of the instrument. Charged hydrogen and helium beams are easily obtained from Van de Graaff accelerators. However, generation of neutral beams poses a significant challenge. The experimental arrangement to be used during the tests at University of Lowell (1-4 MeV $^{+}$H and ^{o}H) and Yale University (5-20 MeV $^{+}$H and ^{o}H and 5-40 MeV $^{++}$He, $^{+}$He and ^{o}He) accelerators is shown in Fig. 2.

A charged beam from a Van de Graaff is made to traverse a carbon foil of areal density of approximately 20 $\mu g/cm^2$. Some of the beam particles pick up an electron from the foil and become neutral atoms. The dipole magnet, located downstream of the foil, bends the charged fraction of the beam to a chamber where the beam intensity can be monitored. The neutral particles continue undeflected through the magnet and exit through the 0^{o} port into the neutral particle detector. If the response of the detector to charged particles is desired, the beam-neutralizing carbon foil is removed and the dipole magnet is switched off so that the charged beam exits through the 0^{o} port and into the detector.

3. NEUTRAL BEAMS

3.1 Neutral Fraction Following Beam-Foil Interaction

In order to produce neutral beam bombardment of the detector, the neutral particles must be produced in the neutralizing foil and the resulting beam must be transported to the detector. This section will be concerned with the production of the neutral particles. The following section, Section 3.2, will address the question of beam transport.

Neutral particles are produced by the pickup of the foil electrons by charged beam particles. A singly charged particle (i.e., $^{+}$H or $^{+}$He) moving through a medium has a cross section for electron capture, σ_C, and once it has captured an electron, a cross section for its subsequent loss, σ_L. It can be directly shown that the neutral fraction, f_o, of an initially charged beam after traversing a distance x in a foil is given by

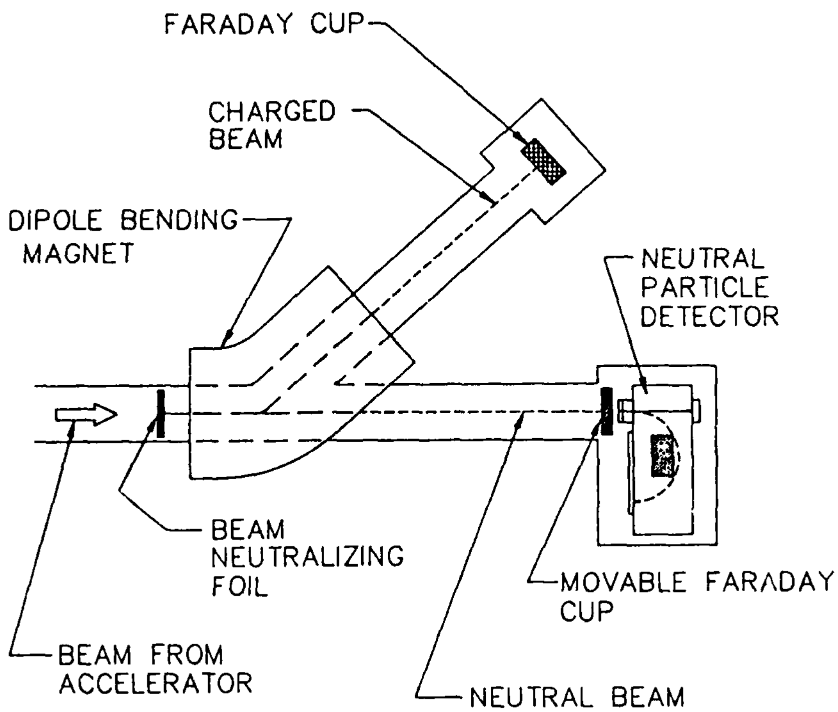


Fig. 2

Experimental set-up to be used during accelerator tests.

$$f_o(x) = (\sigma_C/(\sigma_L + \sigma_C))*(1 - \exp\{-(\sigma_L + \sigma_C)\, Nx\}) \ , \tag{1}$$

where N is density of atoms of the foil material.

The capture and loss cross sections for protons can be expressed as functions of proton velocity using the Brandt-Sizmann theory (Ref. 1):

$$\sigma_C = \pi\, a_o^2 \left[\frac{2^{18}}{5}\right] Z^5\, V^{-6} \left[V^2 + 2^6 \cdot 40^{-1/3}\, Z^{14/9}\right]^{-3} \tag{2}$$

$$\sigma_L = \pi\, a_o^2 \left[\frac{Z^{2/3}}{Z^{2/3} + V}\right] \cdot \left[\frac{4\, Z^{1/3}\,(Z + 1)}{4\, Z^{1/3}\,(Z + 1) + V}\right] \tag{3}$$

where a_o is the Bohr radius, Z is the atomic number of the foil material and V is the velocity in atomic units (1 atomic velocity unit = 2.18 * 10^8 cm/sec). Evaluating equations (2) and (3) shows that σ_L is of the order of 10^{-17} cm^2 for proton energies between 1 and 20 MeV while σ_C decreases rapidly from 10^{-20} to 10^{-25} cm^2 in the same energy range (see Fig. 3). Therefore, for foils thick enough to permit charge equilibration, equation (1) reduces to

$$f_o = \sigma_C/\sigma_L \ . \tag{4}$$

The neutralizing carbon foils to be used in this work have areal densities of at least 20 $\mu g/cm^2$, sufficient to permit charge equilibration.

3.2 Neutral Beam Transport

In addition to producing a neutral beam component, the beam-foil interaction also produces angular dispersion of the beam by the process of multiple scattering. The root-mean-square (rms) scattering angle of a proton, with energy E, incident on a target with atomic number Z and areal density of atoms N is given by (Ref. 2)

$$\theta^2_{rms} = \frac{N\pi Z(Z + 1)e^4}{E^2} \cdot \ln\left[\frac{4\pi N a_o^2}{(1 + Z^{2/3})} \cdot \frac{Z + 1}{Z}\right] \tag{5}$$

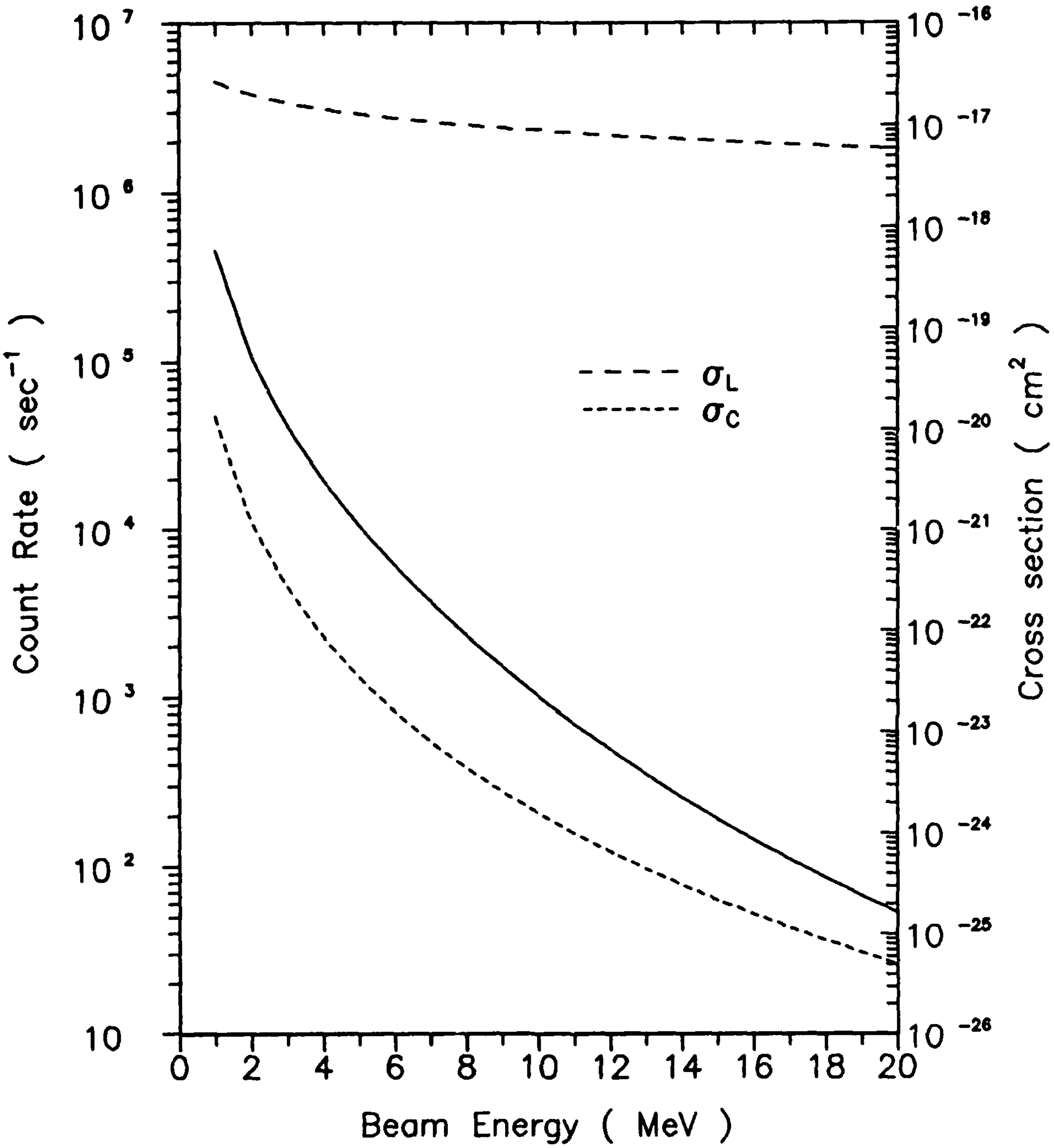


Figure 3.

The solid line is the rate of neutral particles, per each nA of beam, reaching the detector. The dashed lines are the electron loss, σ_L, and capture, σ_C, cross sections of the Brandt–Sizmann theory.

The angular distribution is to a good approximation a Gaussian, with the standard deviation well approximated by the rms angle. The angular spread of the neutral beam component may be somewhat different from that of the charged component, since there exist two additional effects that contribute to scattering of the neutral particles. One effect, the decrease in multiple Coulomb scattering for neutral particles, will tend to make the rms scattering angle smaller, while the other, pick-up of transverse angular momentum during electron capture, will tend to make it larger. Both effects are small in magnitude at the beam energies of interest, and eq. (5) can be expected to be a good estimate of the rms scattering angle for the neutral beam.

The distance between the beam neutralization foil and the detector is large. For the University of Lowell tests, this distance will be approximately 90 inches. This is due to the fact that the beam must go through a large dipole electromagnet which bends the charged beam component away from the detector. The entrance aperture to the detector has a diameter of 3 mm, so that even the small rms scattering angle, typically of the order of 0.05° for 1-20 MeV protons in carbon foils, can lead to a large loss of neutral beam intensity in the detector. Therefore, a correction to the yield calculated with eq. (3) must be made to include effects of beam dispersion. Figure 3 shows the results of such a calculation, the expected number of neutral hydrogen particles that enter the detector per second per nA of proton beam. The losses due to multiple scattering are calculated for the geometry to be used at the University of Lowell tests. The geometry to be used at higher energy tests to be done at the Yale University ESTU accelerator will be very similar.

4. CALCULATION OF CONVOY ELECTRON YIELDS

The expected yields of convoy electrons for incident protons and neutral atomic hydrogen can be estimated using a simple model of convoy electron production. The model assumptions are as follows:

(1) Convoy electron candidates are produced by stripping electrons from neutral hydrogen atoms traversing the target.

(2) Once an electron is stripped off, it moves initially with the projectile velocity, but suffers angular scattering and energy straggling due to collisions with the target atoms.

(3) Only those electrons which suffer little or no angular scattering and energy degradation are experimentally identified as convoy electrons.

In view of the first assumption, incident protons can only produce convoy electrons following a capture of a foil electron. The convoy electron yield per incident beam particle, N_e, can be expressed within the framework of this model, by

$$N_e = \int_0^{x_o} F_o(x) P_e(x_o - x)\ dC(x) \tag{6}$$

where x_o is the total foil thickness, $F_o(x)$ is the fraction of particles in the neutral state at a distance x in the foil, $P_e(x_o - x)$ is the probability of unscattered transmission through the foil of an electron with the beam velocity and dC(x) is the probability of a neutral particle undergoing an electron-stripping collision in a thin section of foil, between x and x + dx.

The expressions for the neutral fraction of the beam are taken from the work of Gaillard et al. (Ref. 3). For an incident neutral atomic hydrogen beam, as function of time of transit through the foil (t_D, dwell time), the neutral fraction, F_H is given by

$$F_H(t_D) = f_o + (1 - f_o) \exp(-t_D/t_o) \tag{7}$$

while for an incident proton beam the expression is

$$F_p\ (t_D) = f_o\ (1 - \exp(-t_D/t_o)) \tag{8}$$

where f_o is given by eq. (4) and t_o is the effective neutral hydrogen "lifetime" in the foil. Gaillard et al. (Ref. 3) have found that t_o is to a good approximation a constant in the energy range of interest and

$$t_o = 2.12*10^{-16}\ \text{sec} \quad . \tag{9}$$

The difference between f_o and F is that while f_o is the neutral fraction following a passage through a thick foil, F_H and F_P are valid even for very thin foils where charge equilibration does not occur. It can be verified directly from eqs. (7) and (8) that in the limit of long dwell times $F_H = F_P = f_o$, as is required.

The electron transmission through a foil, without appreciable angular dispersion and energy straggling, is assumed to be described by the expression

$$P_e(x) = \exp(-\mu x/v) \tag{10}$$

where μ is electron velocity divided by its mean free path in the foil. The parameter μ is, in the electron energy range of interest, approximately independent of velocity (Ref. 4). A value of $\mu = 7.5*10^{15}\ \text{sec}^{-1}$, measured by Latz et al. (Ref. 5) was used in this calculation.

The probability that a neutral hydrogen atom will suffer an ionizing collision after a distance x in the foil is

$$C(x) = 1 - \exp(-\sigma_L N_x) \tag{11}$$

The above expression does not include contributions from multiple stripping and pickup processes. This is justified by the fact that these processes are not important since $\sigma_L >> \sigma_C$. Finally, in a section of foil of thickness dx, the differential ionization probability is given by

$$dC(x) = \sigma_L Ndx = \sigma_L Nvdt \tag{12}$$

Eq. (6) can be solved analytically using the functional forms given in eqs. (7, 8, 10, 12). The solution for incident protons is

$$N_e^P = \frac{f_o}{t_o}\left[\frac{1}{\mu}\quad 1-\exp(-\mu t_D) \quad - \left(\frac{t_o\mu-1}{t_o}\right) \left|\exp(-t_D/t_o) - \exp(-\mu t_D)\right|\right] \tag{13}$$

while for incident neutral atomic hydrogen it is

$$N_e^H = \left[\frac{1}{t_o} \quad \frac{f_o}{\mu}\left(1-\exp(-\mu t_D)\right) + \left(\frac{t_o\mu-1}{t_o}\right)\left|\exp(-t_D/t_o) - \exp(-\mu t_D)\right|\right] \tag{14}$$

Fig. 4 shows the expected convoy electron count rates in the detector given a beam rate of 10 KHz in the detector for foils of areal densities of 2 $\mu g/cm^2$ and 5 $\mu g/cm^2$. The solutions to eqs. (13) and (14) have been multiplied by an efficiency factor of 0.14, which includes effects of geometry as well as the intrinsic MCP detection efficiency for electrons (Ref. 6).

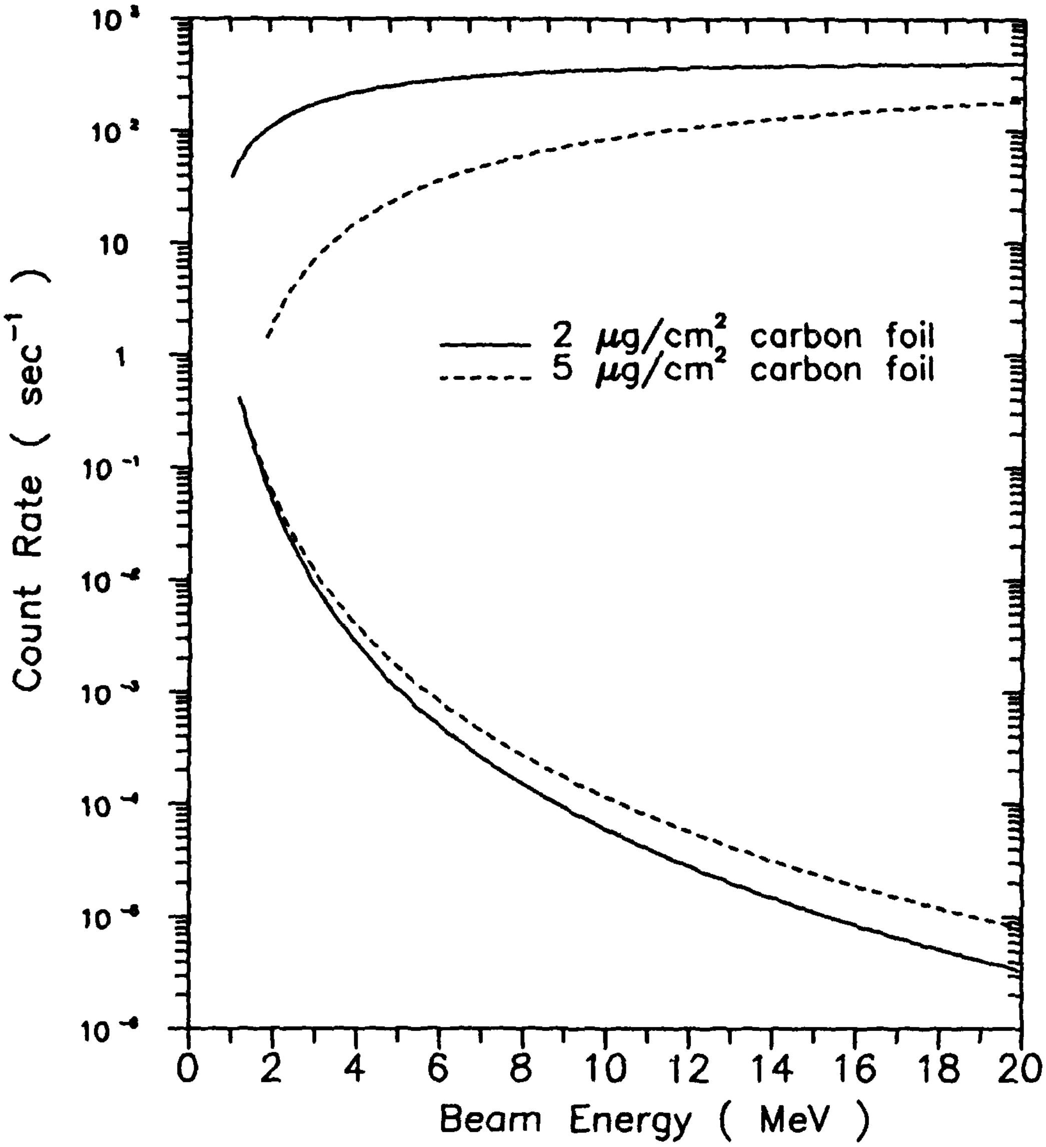


Figure 4.

Calculated convoy electron count rates assuming a 10 KHz particle rate into the detector. The top curve of each set corresponds to an incident neutral beam and the bottom one to a charged beam.

5. SUMMARY AND CONCLUSIONS

The results of the calculations of Section 4 indicate that neutral/charged particle differentiation can be accomplished over a wide energy range. The discussion of these results can be naturally divided into two parts, low energy (1-3 MeV) and high energy (above 3 MeV) results. Each energy region has different experimental requirements.

In the low energy region, it is critical that the thinnest possible foil be used. At an energy of 1 MeV, the electron yields from charged and neutral incident particles become experimentally indistinguishable for a 5 $\mu g/cm^2$ carbon foil while for a 2 $\mu g/cm^2$ foil they differ by nearly two orders of magnitude. In this energy region, it is relatively easy to generate intense neutral beams (see Figure 3) so that even small count rate differences can be accurately measured. It should thus be possible to experimentally verify the charged/neutral particle separation capability. However, a detector on a spacecraft may have to accumulate a large number of counts to allow a statistically meaningful separation of charged and neutral particles.

In the high energy region the foil thickness is not very important since the electron yields from charged and neutral particles are orders of magnitude different for even 5 $\mu g/cm^2$ foils. The experimental challenge lies in the generation of a sufficiently intense neutral beam. The production of neutrals falls off very rapidly with increasing energy so that the 10 kHz rate assumed for the curves in Figure 4 is unrealistic at the higher energies. Thus, the verification of the charged/neutral particle separation at an accelerator is more difficult. However, a detector on a spacecraft may be capable of making a meaningful separation of charged and neutral particles with very few incident counts.

The data that will be collected during the accelerator tests will enable an accurate determination of convoy electron production rates from neutral and charged incident particles. These rates can in turn be used to calculate the lowest level neutral particle flux that can be measured in space for a given operating time and a given charged particle flux. With this information in hand, a detailed design of an instrument for measuring charged and neutral particle fluxes from a spacecraft can be made.

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